Interactive spatial audio diffusion: The pendulum haptic interface prototype

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Abstract. We present a prototype of a tangible tabletop controller for spatial audio based on physical pendulums. The controller, designed for musicians and sound designers, features two independent pendulums mapped to various musical parameters. Manipulating each pendulum enables spatial diffusion of sound. Equipped with a custom board and IMU sensor (MPU 9250), the pendulum detects motion and capacitive touch sensing, including taps. An ESP32 microcontroller with WiFi connectivity gathers sensor data and enables wireless transmission. Angles of the pendulums are calculated from raw data and mapped to musical parameters, allowing users to create musical compositions. The arpeggio mode produces notes based on pendulum angles, while the phasing mode enables phasing and beating effects. This prototype, developed in collaboration with Tangible Music Lab, demonstrates the potential for a 20-channel spatial audio setup called Dodecaotto, a dodecahedron-shaped multichannel system.

Keywords: haptic interface · spatial audio · interactive audio application · physical instrument · musical expression

1 State of the art

Spatial audio can offer an immersive experience, and it is widely used in music, cinema, and games [9, 11, 15]. Variety of both commercial [3] and open-source software for spatial audio exists [4, 7, 14]. There is ongoing research in gestural control or examining controlling the process using gestural control [12] or examining visual and haptic feedback [8]. However, intuitive control of spatialization in the mixing process or during artistic performance still remains unsolved.

We want to create a more intuitive interface that could be used primarily for controlling spatial diffusion and secondary can be used as a musical instrument. Pendulum-based musical instruments were explored in experimental music [16] in the past. The harmonograph is a pendulum-based apparatus able to visualize

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periodic motion and vibrations [18] or Lissajous figures [13], both deeply connected with the nature of music. Haptic pendulum controllers can be based on lasers [10] or inertia measurement units [17].

We aim to create a controller that provides ample interactivity while maintaining simplicity. The pendulum can benefit from executing periodic motions and being intuitively operated. Subsequently, the pendulum's motion can be mapped to spatial sound or used to control music parameters.

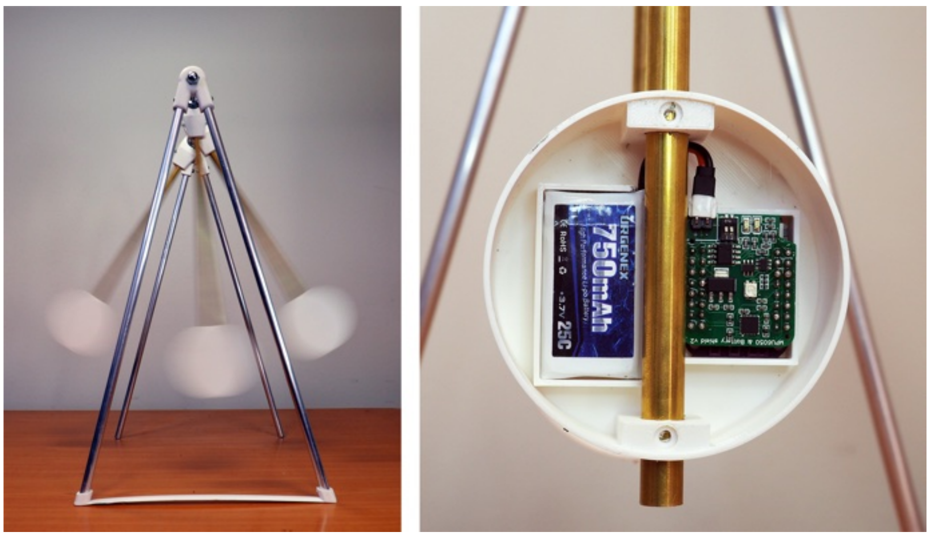

Fig. 1: Left: Three arm pendulum in motion Right: Module and a battery

2 Hardware

See Figure 2 for a data flow diagram overview. We have developed two versions of the prototype. In the first iteration, we collaborated with Tangible Music Lab [3] and constructed the pendulum arm using brass to ensure sufficient weight for longer periodic movements. At the pivot point, we placed an IMU[4] (MPU 6050) sensor, which includes an accelerometer and gyroscope. The ESP32 microcontroller processes the data from the IMU and wirelessly transmits it via WiFi 100 times a second. For power, we used a standard 5V adapter.

In the second prototype, we opted for a modular design, allowing the addition of arms as interchangeable modules. A battery supplies power, and we used a Lolin board [5], compact ESP32 chip, with a custom-made shield 1 providing

[3] https://tamlab.kunstuni-linz.at
[4] Inertial measurement unit

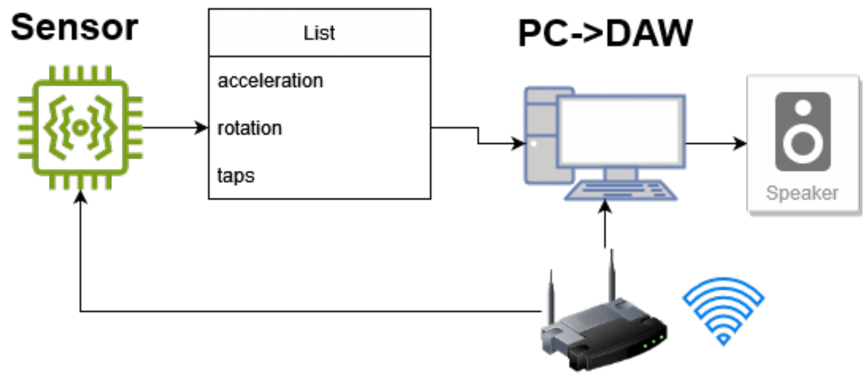

Fig. 2: Data flow from the sensor to the PC and speakers.

battery management and onboard IMU. This setup was chosen for its cost-effectiveness and compact dimensions. The construction incorporates aluminum and 3D-printed parts, making the entire device easy to assemble and portable.

We utilized integrated capacitive switches of ESP32, and connected them to the brass rod of the pendulum. The sensitivity can be calibrated, enabling the entire pendulum arm to be a controller. The MPU6050 chip has a Digital Motion Processor (DMP), which calculates and detects taps in various axes. This feature can be beneficial for interacting with the pendulum's payload, such as stopping it by hand or tapping on the enclosure.

2.1 Data processing and calibration

From the raw data, we calculate the angle of each pendulum. We send quaternions for each pendulum arm to reduce transferred data and to mitigate the gimbal lock [6]. We have developed an application that ensures the connection initialization and visually represents each pendulum arm. This application preprocesses the raw data from IMU and sends pendulum angle as OSC [5] messages to DAW for sound synthesis and spatialization.

The application includes a calibration feature to compensate for the absence of a magnetometer in the MPU6050, which can cause readings deviations. Additionally, achieving perfect alignment of the module parallel to the ground may not always be possible. Through software calibration, the current position of each pendulum is established and identified as the equilibrium position. It is crucial to perform this calibration stationary to ensure precise measurements.

[5] Open-sound control

3 Spatialization

We have used Ableton Live 11 [2], a popular DAW for sound generation, and SpatGRIS software [4] for spatial diffusion. Both of these software can receive OSC messages. For Ableton we have developed custom Max for Live modules for this purpose. Ableton sends audio via Blackhole audio loopback driver [1] to spatial audio engine SpatGRIS. SpatGRIS receives OSC messages for each audio channel describing the coordinates of the sound source and audio stream. This setup enables to connect up to 128 channels.

3.1 Spatial mapping

We conducted tests based on two fundamental concepts for mapping the pendulum motion to spatialization. The first approach involved directly mapping the pendulum's position and motion to a virtual space, allowing the pendulum's position to control the sound source using a Cartesian coordinate system (see 3. As the pendulum reaches its equilibrium position, it coincides with the listener's position in the center of the virtual soundscape. One pendulum influenced the left-to-right movement, while the other affected the forward and backward motion. In cases where three pendulums were used, an additional pendulum controlled the up-and-down position. Skillful coordination of pendulum oscillations could enable the user to achieve circular or elliptical motion, as the pendulum ensures a smooth movement trajectory.

In addition to the above, we explored a more complex motion mapping where the pendulum's displacement from its equilibrium state affected the amplitude and direction of a circular trajectory. In this setup, one pendulum was mapped to the radius and direction of the circular sound source movement. When the pendulum was maximally displaced to one side, it induced a clockwise circular motion. When displaced to the other side, it resulted in the maximum radius in the counterclockwise direction. The pendulum's swinging caused periodic changes in the circular trajectory direction, creating a serpentine path. To enhance the experience further, the second pendulum was mapped to the z-axis, determining the sound's position up or down. Such mapping can produce complex patterns that would be difficult to achieve otherwise.

4 Data sonification

Arpeggio repeats the same note in the initial angle, and each pendulum changes the note when displaced from the initial angle. Each half is divided into specific virtual segments, each corresponding musical note. Clockwise movement is mapped to higher notes, and counterclockwise movement is mapped to lower notes. When the pendulum swings full range, the arpeggio is played in its entirety. When the pendulum performs shorter arc, only part of the arpeggio is played. The user can create sequences by swinging the pendulum or holding each pendulum at the same or different angle.

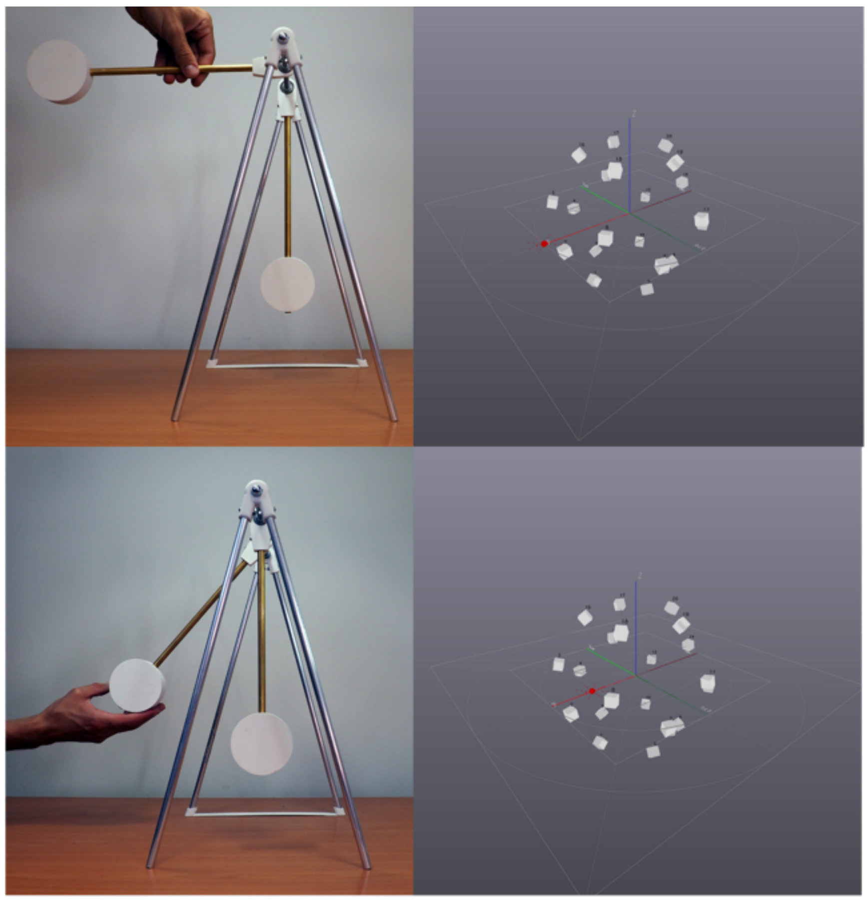

Fig. 3: Direct mapping of pendulum position.

Phasing is inspired by Steve Reich's compositions, such as Piano Phase (1967). Each pendulum controls and detunes its oscillator, enabling users to create phasing and beating effects. This results in binaural beats when headphones are used or various phasing effects when playing physical spatial setups.

Wavetable scanning The pendulum can also be utilized as a sound-shaping instrument. Wavetable synthesis fits this purpose. Tables with stored sounds can be scanned by the pendulum's movement, either towards one side or the other. Multiple pendulum arms allow for the scanning of multiple sounds, facilitating collaboration among several individuals or the exploration of diverse sound possibilities.

Step Sequencer Pendulum motion can act as a step sequencer. As the bar travels, it triggers samples at a given angle. Users can directly modify the sequencer's tempo by adjusting initial velocity or scrub through the timeline by dragging the pendulum by hand.

(a) User testing

(b) Dodecaotto

5 Main benefits & limitations

Using a pendulum instead of a more traditional musical interface, such as pads with buttons or knobs, ensures inherent rhythm and easing. Regular oscillation invites users to explore the harmonics between two or more pendulums with added real-time visual feedback. When paired with auditory feedback, it provides an intuitive interface for complex spatial audio diffusion. Although the prototype can be extended with additional arms for mapping multiple sound sources, the interface does not allow complete software control, such as timeline manipulation or master volume control. However, our designed hardware prototype allows the use of a capacitive rod and tap function, making it possible to implement software features such as switching sound sources during spatial audio mixing or additional control of sound effects. Other controllers might be needed in complex concerts.

6 Pilot study

The initial testing (see 4a occurred within the Dodecaotto, a 20-channel system shaped like a dodecahedron (see 4b), developed as part of the Ottosonic project. This unique setup envelops the user with speakers, offering precise sound localization and ample volume. The testing was conducted during a seminar with Tangible Music Lab students and volunteers. For the tests, we selected the music compositions mentioned earlier.

Furthermore, we explored the pendulum's potential during a concert using an eight-speaker setup arranged in a circular formation. In this concert setting, the pendulum controlled spatialization and triggered selected sounds upon touching its arms. A different sound was also produced when both pendulum arms passed each other. Throughout the performance, we alternated between various sound setups, such as arpeggio, as previously mentioned, or scenarios where the displacement of one pendulum influenced sound effects, while the other pendulum determined the sound's pitch. To ensure the audience could observe the direct interaction with the pendulum and its corresponding sound representation, intentionally simpler sounds were chosen.

7 Conclusion

We have created a proof-of-concept interface for controlling spatial sound by directly manipulating the pendulum. Complex patterns can emerge from the simple rules assigned to pendulum motion, especially with multiple pendulums used. We are leveraging the natural periodicity of pendulum motion to spatialize the sound. Moreover, we can also directly synthesize the sound from the pendulum motion. Using a physical interface with intuitive haptic feedback, we democratize sound mixing for the wider public without specialized technical know-how. Even professional musicians can benefit from the proposed controller as it provides complex musical gestures.

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References

1. BlackHole: Audio loopback driver, https://github.com/ExistentialAudio/BlackHole, original-date: 2019-09-27T18:40:46Z
2. Creative tools for music makers | ableton (2023), https://www.ableton.com/
3. Dolby atmos - official site (2023), https://www.dolby.com/technologies/dolby-atmos/

4. GRIS – sound spatilialization (2023), http://gris.musique.umontreal.ca/
5. S2 mini — WEMOS documentation (2023), https://www.wemos.cc/en/latest/s2/s2_mini.html
6. Alaimo, A., Artale, V., Milazzo, C., Ricciardello, A.: Comparison between euler and quaternion parametrization in UAV dynamics. pp. 1228–1231. https://doi.org/10.1063/1.4825732, https://pubs.aip.org/aip/acp/article/1558/1/1228-1231/801988
7. Carpentier, T., Noisternig, M., Warusfel, O.: Twenty years of ircam spat: looking back, looking forward. In: 41st International Computer Music Conference (ICMC). pp. 270–277 (2015)
8. Gelineck, S., Overholt, D.: Haptic and visual feedback in 3d audio mixing interfaces. In: Proceedings of the Audio Mostly 2015 on Interaction With Sound. pp. 1–6. AM '15, Association for Computing Machinery. https://doi.org/10.1145/2814895.2814918, https://dl.acm.org/doi/10.1145/2814895.2814918
9. Guastavino, C., Larcher, V., Catusseau, G., Boussard, P.: Spatial audio quality evaluation: comparing transaural, ambisonics and stereo. Georgia Institute of Technology (2007)
10. Henson, J., Collins, B., Giles, A., Webb, K., Livingston, M., Mortensson, T.: Kugelschwung-a pendulum-based musical instrument. In: NIME
11. Melchior, F., Spors, S.: Spatial audio reproduction: from theory to production. In: tutorial, 129th Convention of the AES (2010)
12. Quiroz, D.: Gestural control for 3d audio. 3D Audio pp. 64–81 (2021)
13. Romer, R.H.: A double pendulum "art machine" **38**(9), 1116–1121. https://doi.org/10.1119/1.1976562, https://pubs.aip.org/aapt/ajp/article/38/9/1116-1121/1048724
14. Rudrich, D.: IEM plug-in suite (2023), https://plugins.iem.at/
15. Rumsey, F.: Spatial audio. Taylor & Francis (2012)
16. Senn, D.: Pendulum-based instruments, percussive video, sound art, and the permanence of ephemeral public art **2**(3), 151–163. https://doi.org/10.1017/S1355771898009017
17. Skarha, M., Cusson, V., Frisson, C., Wanderley, M.M.: Le bâton: A digital musical instrument based on the chaotic triple pendulum. In: NIME 2021. PubPub
18. Whitaker, R.J.: Harmonographs. i. pendulum design **69**(2), 162–173. https://doi.org/10.1119/1.1309521, https://pubs.aip.org/aapt/ajp/article/69/2/162-173/1030296